Properties of tool and task determine young childrens affordances

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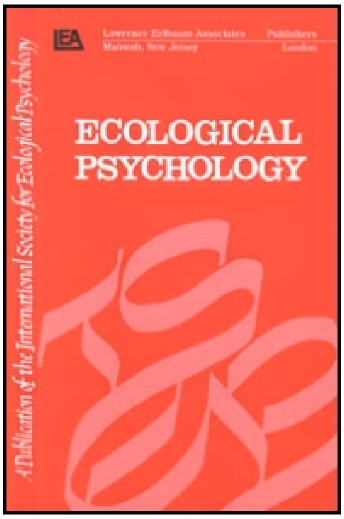

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Geometric, But Not Kinetic, Properties of Tools Affect the Affordances Perceived by Toddlers

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We asked what rod properties affected children's reaching range. Children, 2 to 4 years old, held a rod (length 10–60 cm) with the tip in the air, walked toward a toy on a table, chose a place to stop, and displaced the toy with the rod's tip. In 2 experiments rod length, mass, and mass distribution were manipulated to determine whether and how geometric and kinetic properties affected chosen distance and posture. Chosen distance depended only on the length of the rod. Postures were affected by length and mass properties of the rod. Not all adaptations in posture were prospec-

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tively reflected in the distance. Although we found variations over age, we did not find clear developmental trends. The results are discussed in broader perspectives of development of affordances and tool use.

Humans rely extensively on tools to alter their capacities for action when performing the diversity of tasks required in everyday life. Tools can be defined as objects that can be attached to the body to adjust the capacity for action. However, the change in action possibilities with implements has tended not to be the focus of most studies of tool use. In this article we concentrate on the change of action possibilities with tools, and we take the ecological approach to perception and action, inspired by J. J. Gibson (1966, 1979/1986), as a framework to do this. A core concept of ecological psychology is the concept of affordances, which are defined as the possibilities for action provided to a given person by an environmental layout (J. J. Gibson, 1979/1986). Tools, in particular, change action possibilities, and we start from the working hypothesis that tools change affordances (J. J. Gibson, 1979/1986; Hirose, 2002; cf. E. J. Gibson & Pick, 2000; Lockman, 2000; Smitsman, 1997; Smitsman & Bongers, 2003; Van Leeuwen, Smitsman, & Van Leeuwen, 1994; Wagman & Carello, 2001). Affordances can be perceived, and in this article we address how the perceptual attunement to affordances with tools develops. We studied the properties of tools that determine affordances for children and whether those properties change over age. We examined how children used a rod to reach for and displace an object, and we examined how actions were affected by properties of the rod. The properties of the rods we varied in the experiments were rod length, rod mass, and mass distribution.

How do tools affect young children's reaching actions? McKenzie, Skouteris, Day, Hartman, and Yonas (1993) showed that for seated infants a wooden spoon did not extend the reaching range by its full length, suggesting that variables other than length are also important. To examine what those variables might be, in this study we varied both length and mass properties of the tool. Moreover, McKenzie et al. showed that the capacity to perceive the range reachable with an implement changed with age; 10-month-old infants had more difficulty perceiving how much a spoon extended their reaching space than did 12-month-old infants. In this study we tested older children, 2 to 4 years old, who, we think it is fair to say, use more and more implements to explore and to act. Hence, we expect that children in that age range are developing the capacity to perceive new affordances when properties of tools change.

How can one assess whether affordances of a handheld rod are perceived? Before we can answer this, it is useful to consider how tools affect affordances. Affordances are the action possibilities in the environment, and they have their counterpart in the organism: the possible ways the action system can be organized into functional units. These are called effectivities (Shaw & Turvey, 1981; Turvey & Shaw, 1979) and can be considered as the means by which an affordance may be seized. Hence, body + tool can be understood as a change in the effectivity (cf. Hirose, 2002; Shaw, Flascher, & Kadar, 1995; Smitsman, 1997). Note that changes in effectivities should be revealed in the available postures, which in turn depend on the forces and torques that a tool creates. Hence, to examine how properties of a tool affect effectivities—and, thus, affordances—we examined how posture changes as a function of the tool properties. To manipulate available postures, we varied kinetic properties of the rod that are affected by mass and mass distribution.

If affordances are indeed perceived, then the effect of variations in available postures should be apparent in early phases of the act; that is, there should be prospective changes in the action. What sorts of prospective changes might occur in the present task? Children walked toward a small table while pointing a rod upward about 45° and selected a place to stop—some distance from which they could displace a toy duck on that table. They then lowered the rod and with the tip of the rod slid the duck off the table into a basin of water. Note that the stopping place could not be determined on the basis of a strategy of closing the gap between the rod's tip and the object because the stopping place was chosen with the rod pointing upward. The task implied prospective control on the basis of rod length and/or posture needed to control the rod during displacement. Hence, changes in the selected distance indicate the characteristics of the body + tool system that affect the affordances.

Adults can do this task with ease. Our earlier work showed that, when adults performed this task, both the selected distance to the table and the posture during displacement depended on the length, mass, and mass distribution of a rod and on size of the to-be-displaced object (Bongers, Michaels, & Smitsman, 2004; Bongers, Smitsman, & Michaels, 2003). These findings show that both the geometrics (lengths) and the kinetics (mass and force properties that determined posture) of the body + tool system were of importance for selecting a distance to displace an object, implying that both length of the rod and required posture are anticipated in the selected distance. Hence, this indicates that adults perceived the affordances in the tool-using task and acted prospectively. In the research reported in this article we studied whether children also change their stopping place according to variations in length and available posture.

Children, of course, have much less experience with tools than do adults. We expected children from 2 to 4 years old, the age range of our participants, to vary considerably in this respect. This should ensure a range of age-related differences in the capacity to perceive rod affordances. In other words, the pickup of affordances is learned over development, which implies that not all affordance-related tool properties will affect children early in development (cf. E. J. Gibson & Pick, 2000). In this study we focused on geometric and kinetic properties of tools, and we examined whether there are age-related changes in the pickup of information specifying those tool properties.

The way we changed the kinetics of the body + tool system is not unlike the method of Adolph and Aviolo (2000), who changed body dimensions by attaching weight to children's backs. Young children had more difficulty selecting a traversable slope when the attached weight was heavier. This implied that they had more trouble adapting actions to new properties of the action system. Learning to constrain the degrees of freedom in the action system to fit the properties of the environment is a basic problem children face when performing goal-directed actions (cf. Adolph, 1997; Adolph, Eppler, & Gibson, 1993; E. J. Gibson & Pick, 2000; Ulrich, Thelen, & Niles, 1990). We think that changing the dynamics (i.e., kinetics) of the action system, such as taking up a tool, poses a particular action problem that children must learn to solve (cf. Lockman, 2000; Smitsman & Bongers, 2003).

Note that the change in affordances that occurs when one uses a tool has a number of factors in common with the change in affordances that occurs because of bodily growth. Growth, such as an increase in length and mass of limbs, affects the forces and torques in the action system. A handheld object also modifies forces and torques in the joints and muscles, and hence new affordances may arise. These similarities suggest that studying tool use in young children may provide a special glimpse into more general developmental processes associated with growth. However, we are aware that there are differences in time scale (i.e., growth takes time; changes due to tools are instantaneous) and in continuity (i.e., growth is gradual; picking up a tool results in abrupt changes) of the change of action possibilities. Still, we are hopeful that the study of how children perceive the changes may provide insights into how children perceive the action consequences of the (slowly changing) geometric and dynamic properties of their bodies (for a more elaborate discussion of this issue, see Smitsman & Bongers, 2003).

An important difference between this study and other studies of tool use is that we approached tool use as a perception–action problem instead of as a cognitive problem (cf. Smitsman, 1997; Smitsman & Bongers, 2003; for a similar approach, see Hirose, 2002; Lockman, 2000). Studies of tool use have traditionally focused on problem-solving abilities; that is, tool use has been studied to uncover cognitive mechanisms, particularly how mental capabilities of planning and problem solving can develop in children (Bates, Carlson-Luden, & Bretherton, 1980; Köhler, 1925; cf. Lockman, 2000; McCarty, Clifton, & Collard, 1999; Steenbergen, Van der Kamp, Smitsman, & Carson, 1997; Van Leeuwen et al., 1994). However, a strictly cognitive approach easily neglects the perceptual- and motor-related aspects that are involved in tool use (cf. Thelen, Schöner, Scheier, & Smith, 2001). A child who is developing the ability to use a tool has to discover how to constrain the degrees of freedom in the action system given the geometric and kinetic properties of the tool. These changes, in turn, affect affordances, and we asked whether young children perceive the new affordance.

A large body of research has established that adults can perceive changes in geometric and kinetic properties of handheld objects by way of dynamic touch (Solomon & Turvey, 1988; for overviews, see Turvey, 1996; Turvey & Carello, 1995). Experiments have revealed that an object's rotational inertia specifies object properties to a perceiver who holds the object but does not see it. In our case, the rods can be seen, so the contribution of dynamic touch to perceived length was expected to be minimal (Bongers et al., 2003; Pagano, Aten, & Alley, 1998), but there are other connections between dynamic touch and tool use. Wagman and Carello (2001) found that ratings of usability of implements for given tasks (hammering or poking) depended on the object's inertia tensor. Earlier research with adults (Bongers et al., 2004; Bongers et al., 2003) has found that the moments of inertia did not predict the selected distance to the table, but given the importance of haptic perception to detecting tool properties, in this study we examined the contribution of the moment of inertia to the selected distance with children.

Smitsman (1997) established that children adapt their reaching distance to changes in rod length. He showed, in an experiment similar to ours, that the slope of the regression line between rod length and selected distance was 0.66 for 2-year-old children and 0.81 for 3-year-olds. We found roughly the same numbers in a pilot experiment. In this study we expanded the range of independent variables by also manipulating mass properties of the rod. Moreover, our focus was not just on reaching distance but also on whether and how the reaching distance follows from the posture that is used to control the rod and whether such anticipation develops with age.

In short, we were interested in the properties of a tool that determined affordances for young children and how these properties changed with age. In our experiments, children used a rod to displace an object, and we manipulated geometric and kinetic properties of the rods to examine the variables and mechanism underlying the observed changes in action. In Experiment 1 we varied length and mass, and in Experiment 2 we varied length and mass distribution of the rods.

EXPERIMENT 1

Earlier research (Smitsman, 1997) revealed that children chose their stopping place according to the length of the light wooden rod they used to displace a toy. In the following experiments we tried to determine the variables and mechanisms from which this ability originates. In Experiment 1 we manipulated rod length and the homogeneous mass of the rod. We were interested in whether young children changed the reaching distance according to those rod properties and whether this differed over age.

Manipulations of rod length and mass affect the forces and torques in the body; these altered constraints on neuromotor degrees of freedom may require different postures to accomplish the task. In short, changing length and mass may create new postural constraints. To the extent that children show perfect prospective control, any such alterations in posture should be prospectively reflected in the adopted reaching distance; that is, children should select a reaching distance that both accommodates the length of the rod and allows for a posture with which the rod can be controlled.

Postural constraints could affect the action in several ways, three of which are discussed here. First, a heavy rod will displace the center of mass (CM) of the body + rod system in the direction of the rod. This shift in CM could compromise balance and may require compensation. Leaning backward at the ankle or the hip, or more shoulder retroflexion (i.e., having the upper arm behind the shoulder), could offset heavier rods. Second, a heavy rod, especially one creating torques near the maximum of joint moment strength, could severely restrict movement. Chaffin and Andersson (1991) presented equations[1] that predict maximum joint moment strength in any given posture for adults. For each joint, one can compute the expected maximum muscle-produced joint moment that could counteract moments created by external loads. Using these formulas, we modeled our task and found that, if very heavy rods need to be handled, the shoulder should be retroflexed and the elbow moderately flexed. We assume that the same relations hold for young children. More shoulder retroflexion and more elbow flexion would result in a smaller wrist–waist distance, or even the hand behind the shoulder. Such changes should affect early stages in the act, and if their consequences for reaching distance were anticipated, one should select a closer distance to the table for a heavier rod of the same length. Third, changing the mass of a rod changes the wieldability of the rod. To examine the effects of wieldability, we analyzed the contribution of moments of inertia in the reaching distance. The wieldability of the rod is reflected by its moments of inertia, which indicate the resistances to various rotational accelerations.[2] Rods with larger moments of inertia require more torque to wield. The magnitudes of the moments of inertia depend on the mass and the distance between the mass and the axis of rotation; a rod with a larger mass has a larger moment of inertia. In earlier research (Bongers et al., 2004), we found that adults stood closer to the to-be-displaced object with lighter rods. Our interpretation was that a closer distance yielded a posture with which more control over the rod could be exerted; more control is required for lighter rods because a small torque would have a relatively large effect. In short, on the basis of postural constraints related to shifts

[1]Chaffin and Andersson's (1991, pp. 250–251) equations predict maximum joint moment strengths in the sagittal plane. These equations are averages over several studies that measured moment strength, implying that the shape of the function is sound but that the magnitudes can differ for individuals or populations. The equations we used were:

$$ME = (336.29 + 1.544 \times EA - 0.0085 \times (EA)^2 - 0.5 \times SA) \times GA$$
$$MS = (227.338 + 0.525 \times EA - 0.296 \times SA) \times GA,$$

where ME and MS are joint moment strengths for flexion about the elbow and shoulder, respectively; EA and SA are elbow and shoulder angles (defined in the same way as in Experiments 1 and 2); and GA is a gender adjustment.

[2]The explanation of moments of inertia presented here is intended to provide very general reminders of what the moments of inertia represent. For a more mathematically grounded explanation of moments of inertia, see Barger and Olsson (1995), Gere and Timoshenko (1991), and Turvey and Carello (1995).

in CM and to torque in the joints, we expected that a closer distance to the table would be selected with heavier rods, whereas on the basis of the wieldability of the rod, we expected that a larger distance would be selected with heavier rods. Note that adults behaved according to the latter effect; however, it might be that during development the effects of shift in CM or maximum producible torque are more important.

Is it reasonable to assume that 2- to 4-year-old children can control rods that vary in lengths and weight and that they perceive the changes in affordances those rods provide? Research in several paradigms has shown that infants from a very young age prospectively change their actions according to the action possibilities. Research on the development of reaching has shown that infants reach less often for objects when visual information specifies that the objects were beyond their reach (cf. Field, 1976; Yonas & Granrud, 1985). Closer to the task at hand, Riach and Hayes (1990) showed that 4-year-olds prospectively organize their posture according to upcoming joint forces when self-initiating a movement. Findings such as these led us to expect that, in our task, the selected distance to the table would reflect changes in postural constraints and that this differs over children who differ in age. We examined this by comparing children of two age groups.

Although we measured at one point in time (i.e., the selected distance), our interest was in how dynamic aspects of the system (i.e., forces) affected the reaching distance in an anticipatory way and how the posture with which the object was displaced depended on changes in the dynamics. We believe that measuring the behavior at one moment could reveal those changes in the action. However, to make certain that we did not overlook ways in which behavior was prospectively changed, we extended our analyses to an examination of how behavior unfolded in a trial. In those analyses, we examined how children deviated from task instructions. We assumed that children would deviate from the task instruction to solve action problems, for example, either to reduce the problems of selecting the distance or to provide a better means of controlling the rod. Task instructions regarding details of how an action is to be performed are thereby considered as constraints that may be violated to satisfy the task goal of displacing the object.

To summarize, we manipulated the length and mass of rods used to displace a toy. We examined the relative importance of rod length and postural constraints (assumed to follow from kinetics) for the selection of distance and how this develops. From the postural constraints related to the shift in CM, and from the relative maximal torques expected with different postures, we predicted that heavier loads on the arm would lead to more retroflexion in the shoulder and smaller elbow angles and, thus, a closer distance to the table. On the basis of the wieldability of the rod, we predicted that a closer distance would be selected with lighter rods. To study developmental aspects, we examined whether the behavior differed over age.

Method

Participants. Twenty-three preschoolers, ranging in age from 2 years 3 months to 4 years, participated. Two did not perform the task properly (see the Design section). The ages and genders of the remaining 21 are listed in Table 1. Two had participated in such an experiment before. The group of children was divided in two age groups: The 10 younger children ranged in age from 2 years 3 months to 3 years (*M* age = 856 days), and the older children ranged in age from 3 years 3 months to 4 years (*M* age = 1,261 days). All children attended a day-care center linked to the Department of Developmental Psychology of the University of Nijmegen in Nijmegen, The Netherlands. Some of the parents were staff of the university; other parents lived in the vicinity of the university. Parents agreed to their child's participation in experiments when registering them in the day-care center.

TABLE 1
Overview of the Characteristics of the Children Used in the Analyses of the Two Experiments

Experiment 1			*Experiment 2*		
Child	*Age (Years;Months)*	*Gender*	*Child*	*Age (Years;Months)*	*Gender*
1	2;3	f	1	2;2	m
2	2;3	f	2	2;4	m
3	2;4	m	3	2;7	m
4	2;4	f	4	2;8	m
5	2;4	m	5	2;10	m
6	2;5	m	6	2;11	m
7	2;6	m	7	2;11	m
8	2;6	m	8	2;11	f
9	2;7	f	9	3;1	m
10	3;0	m	10	3;2	m
11	3;3	m	11[a]	3;4	m
12	3;3	m	12[a]	3;8	m
13	3;4	m	13[a]	3;9	m
14	3;5	m	14[a]	3;9	m
15	3;5	m	15	3;9	f
16	3;6	m	16[a]	3;10	f
17	3;8	m	17[a]	3;11	m
18	3;10	m	18	3;11	m
19[a]	3;10	m	19[a]	4;1	m
20	3;11	m			
21[a]	4;0	m			

Note. f = female; male = male.

[a]Indicates a child who had participated in a previous experiment in this paradigm. An analysis on the data of Experiment 2 showed that these children did not differ from naïve children, $F(1, 15) = 1.35$, $p > .25$.

Materials. Rods with a diameter of 1.25 cm were used; they ranged in length from 0.1 to 0.4 m, in 0.1 m increments. Three sets of four rods were constructed, one set from wood (density 0.67 g/cm^3), one from solid aluminum (density 2.70 g/cm^3), and one from solid steel (density 7.80 g/cm^3). A handle was added to each rod by extending it 6.5 cm, and a small disc separated the handle from the rod. The rods were painted white to make them look similar, independent of the material. To prevent children from feeling differences among the rod surfaces, PVC tubing was put over the rod handle.

The rod properties used in various analyses are presented in Table 2. We computed the maximum torque that the rod produces in the wrist as the torque at the end of the handle when the rod was held horizontally (i.e., 0°). This was done by multiplying the gravity force acting on the rod's center of mass by the distance between the center of mass and the end of the handle. The moment of inertia was computed with the rotation point in the wrist.

A toy duck (approximately 10 cm wide, 8 cm high, 8 cm in depth, and weighing 44 g) was placed on a table (25 cm × 25 cm) adjusted to each child's wrist height when standing with arms relaxed. The toy was placed against a panel (12.5 cm × 25 cm) such that the toy was flush with the front of the table; the panel ensured that the tip of the rod was used to displace the toy. On the floor to the left of the table stood a small basin of water (35 cm × 35 cm).

A board (2.0 m long and 0.6 m wide) on the floor formed a walkway to the table (see Figure 1). The board had alternate light and dark striping of 5 cm perpendicular to its length. A small rail was created along the long sides of the board by five posts (50 cm high) connected by cord.

Design. In each session, the 12 rods were presented in a random order. Each session was performed on a different day within a 3-week period. Some children

TABLE 2
Characteristics of the Rods Used in Experiment 1

Length (m)	*Type*	*Mass (g)*	*Moment of Inertia (kgm^2)*	*Maximum Torque (Nm)*
0.10	Wood	30	0.00017	0.024
0.20	Wood	37	0.00071	0.047
0.30	Wood	41	0.00163	0.072
0.40	Wood	49	0.00329	0.110
0.10	Aluminum	67	0.00037	0.054
0.20	Aluminum	96	0.00189	0.124
0.30	Aluminum	125	0.00511	0.224
0.40	Aluminum	154	0.01055	0.352
0.10	Steel	164	0.00090	0.133
0.20	Steel	256	0.00506	0.332
0.30	Steel	346	0.01413	0.620
0.40	Steel	436	0.02987	0.995

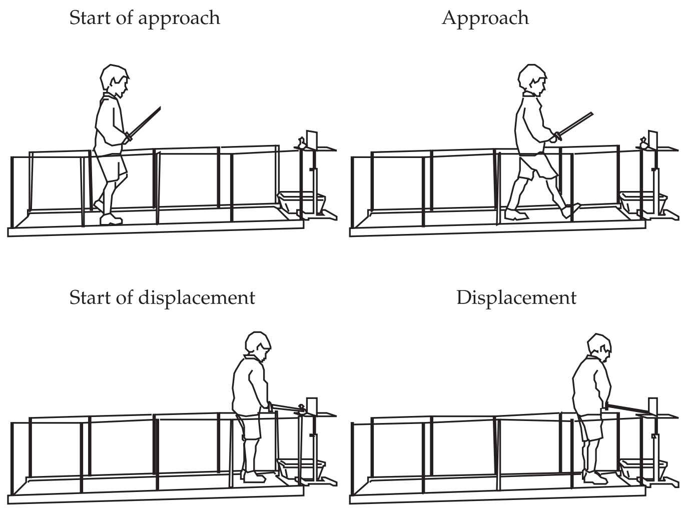

FIGURE 1 Several stages in the unfolding of a trial in which a wooden rod of 0.4 m was used.

were more motivated than others, but we collected as much data as possible; hence, 9 children participated in four sessions (48 trials), and 14 children participated in five sessions (60 trials).

Of the 2 participants whose data were deleted, one used a "sword-fight" posture on most of the trials. In this posture, the legs were spread and the feet were perpendicular to the pointing direction of the rod. The whole body is turned, and one shoulder faced the toy, which was displaced with a stretched arm. The other participant ran or skipped when approaching the target. After the loss of those 2 participants and two additional trials because of technical reasons, the data set comprised 1,162 trials from 21 children (see Table 1).

Procedure. The first session started with a verbal explanation of the task. An experimenter demonstrated the way the tip of the rod could be used to displace the toy. Then the experimenter helped the child in performing the task adequately for three or four practice trials, while repeating the task instructions. After this small practice session, the experiment started. At the beginning of each experimental trial, the steps to follow—approach with rod pointing upward, selecting distance with rod pointing upward, lowering of the rod, and displacement—were verbally repeated. Each new session on a day started with one or two practice trials. The rods for the practice trials were randomly chosen.

On each trial, a rod was handed to the child when he or she was standing at the beginning of the board. The child held the rod in his or her right hand at an angle of about 45° upward from the horizontal and walked toward the table (see Figure 1). The task was to stop at a distance from which they could reach and displace the toy on the table, to lower the rod, and using the tip of the rod, to slide the duck off the table into the water basin. At the end of the last session we measured the height and the weight of each child.

The approaches and reaches were videotaped from the same position as that from which Figure 1 is drawn. For each trial, we selected the first frame at which the object had moved. All the digitizing was done on this frame. We used a video digitizing system—a video frame grabber and a digitizing program developed for movement studies (Welter, Den Brinker, & Van Balkom, 1996)—to compute the positions of handle of the rod, tip of the rod, and the various anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, wrist) in a two-dimensional plane at the moment of object displacement.[3]

Scoring the data. A preliminary examination of the videotapes showed that most of the trials were performed with a pattern illustrated in Figure 1. However, the children did not always follow the task instruction of simply lowering the rod and displacing the duck. Therefore, we evaluated the videotapes to distinguish between trials that were performed according to the instructions and trials that were not. Each trial was scored for (a) the approach to the table, (b) the realization of the actual distance to the table, (c) the posture with which the actual displacement was performed, and (d) the hands that were used. The scoring categories are presented in Table 3. Items scored in the left column of Table 3 were considered to have been completed according to instructions, whereas items scored in the right column were regarded as having been completed contrary to instructions.

One rater (the first author) categorized the trials according to the listed criteria. To establish the reliability of his categorizations, an independent rater scored 4 children's performance in one session. Of the total of 48 trials, 43 were scored the same for the acceptable-approach trials, an agreement on 90% of the trials. For the one-go trials, there was an agreement on 42 trials (88%), and for the one-hand trials, there was an agreement for all the trials (100%). These scores implied that the criteria could be scored fairly reliably.

Dependent variables. Participants were instructed not to move their feet once they started to lower the rod. Therefore, the distance to the table was to remain unchanged during the displacing of the duck. For our measure of body posture during toy displacement, we used the same frame; all the dependent variables were measured at the onset of the displacement of the duck. There were four dependent variables: the selected distance to the table and three measures related to

[3]Because of constraints on the experimental room, it was not possible to film the left side of the participants. Casual perusals during pilot studies showed that, on only a few occasions, children showed a preference to use the left hand. However, asking those children to perform the task with the right hand did not seem to affect their performance. Therefore, children were instructed to use their right hand to hold the rod, independent of their hand preference.

TABLE 3
The Bases of Behavioral Categories

Acceptable Approach	*Aberrant Approach*
1. The rod pointed upward and was lowered when the participant stands still. 2. The rod points upward during the approach and is lowered in the last two steps.	1. The rod is horizontal during the approach, and the participant stops when the tip of the rod is near the table. 2. The rod is horizontal during the approach, and the participant stops when the tip of the rod hits the toy duck or the screen behind it. 3. The tip of the rod drags over the floor or the rod is pointed downward during the approach. 4. During the approach, the child swings the rod in the air. 5. During the approach, the rod is held with two hands. 6. The participant is distracted.
One-Go Distance Selection	*Distance Adjusted*
3. Once the participant stops, no adjustments of the feet are made.	7. The approach is made with the rod pointing upward, but the feet are adjusted when the rod already is lowered. 8. During the approach, the rod is held horizontal, and the distance to the table is based on fine-tuning in the last steps.
Normal Posture	*Awkward Posture*
4. The legs are relatively straight; the bending at the hip is minimal. The arm is stretched out with the wrist almost at hip height. 5. During the displacement of the object, the longitudinal axis of the rod is in the walking direction. To displace the object, the movement of the rod is almost perpendicular to its longitudinal axis.	9. The feet are spread, and the body is turned with one shoulder facing the object (a "sword fighting" posture). 10. The hip is extremely bent. 11. During the displacement of the object, the longitudinal axis of the rod is held parallel to the frontal plane. 12. The elbow is held upward. 13. The wrist is pushed against the body (a freezing of the degrees of freedom in the arm), and the torso is turned to make the displacement possible.
One Hand	*Two Hands*
6. Only the right hand holds the rod.	14. Both the right hand and left hand are used to control the rod. The left hand might be at the handle or farther down the rod.

the posture with which the object on the table is displaced. The *foot distance* reflected the selected distance and was defined as the horizontal distance between the foot nearer to the table and the table. Perusal of the tapes suggested that the general posture is usually upright and that most adaptation takes place in the hip and the arm. Hip angle, shoulder angle, and elbow angle are dependent measures that reflect such adjustments. The *hip angle* measured the bending of the trunk relative to the thigh. A value of zero indicated that the trunk was in line with the thigh. Forward bending (shoulder in front of the hip) had a positive value, whereas backward bending in the hip gave a negative value. The *shoulder angle* was zero when the upper arm was in line with the trunk. Negative angles, also referred to as *retroflexion*, indicate that the upper arm is behind the shoulder, and positive angles indicate *anteflexion*—when the upper arm is anterior to the shoulder. The fully extended *elbow angle* is defined as 180°, and smaller angles denote flexion.

One digitizer determined the positions of the joints and feet. To test the accuracy of his digitizing, a second observer digitized a subset of the trials. The distance between the digitized joint locations by the two observers was averaged over all joints and all 32 trials. The average difference was 1.63 cm (SD = 2.08 cm), which means that most of the points were localized to the same pixel.

Results and Discussion

Behavioral analyses. The way children deviate from task instructions in the unfolding of a trial is informative about how rod properties affect actions prospectively. The alternative solutions children used are listed in Table 3. We examined whether there were systematicities in these alternative solutions that could help identify which properties of the tool determined the affordances. Here we present one representative analysis in which we examined differences in prospective control.

We selected the trials in which children showed prospective control, which were trials with an acceptable approach (trials scored with Items 1 and 2 in the left column of Table 3) and in one go (trials scored with Item 3 in the left column of Table 3). We analyzed whether the percentage of such trials differed over rod conditions with a three-way multivariate analysis of variance (MANOVA) with rod type (wood, aluminum, and steel) and rod length (0.1, 0.2, 0.3, and 0.4 m) as within-subject factors, and age (younger vs. older) as a between-subjects factor. Two main effects were significant: The effect of rod length, $F(3, 17) = 12.01$, $p < .001$, showed that there was prospective behavior on more trials with short rods than with long rods (see Figure 2A), and the effect of age, $F(1, 19) = 8.19$, $p = .01$, showed that young children had less prospective behavior than older children (young = 58%, 95% confidence interval: 49%–68%; old = 76%, 95% confidence interval: 67%–85%). The other significant effect was the interaction between rod length and rod type, $F(6, 14) = 3.16$, $p < .05$. Post hoc tests with Bonferroni corrections showed no significant differences. In general, the effect indicated that the

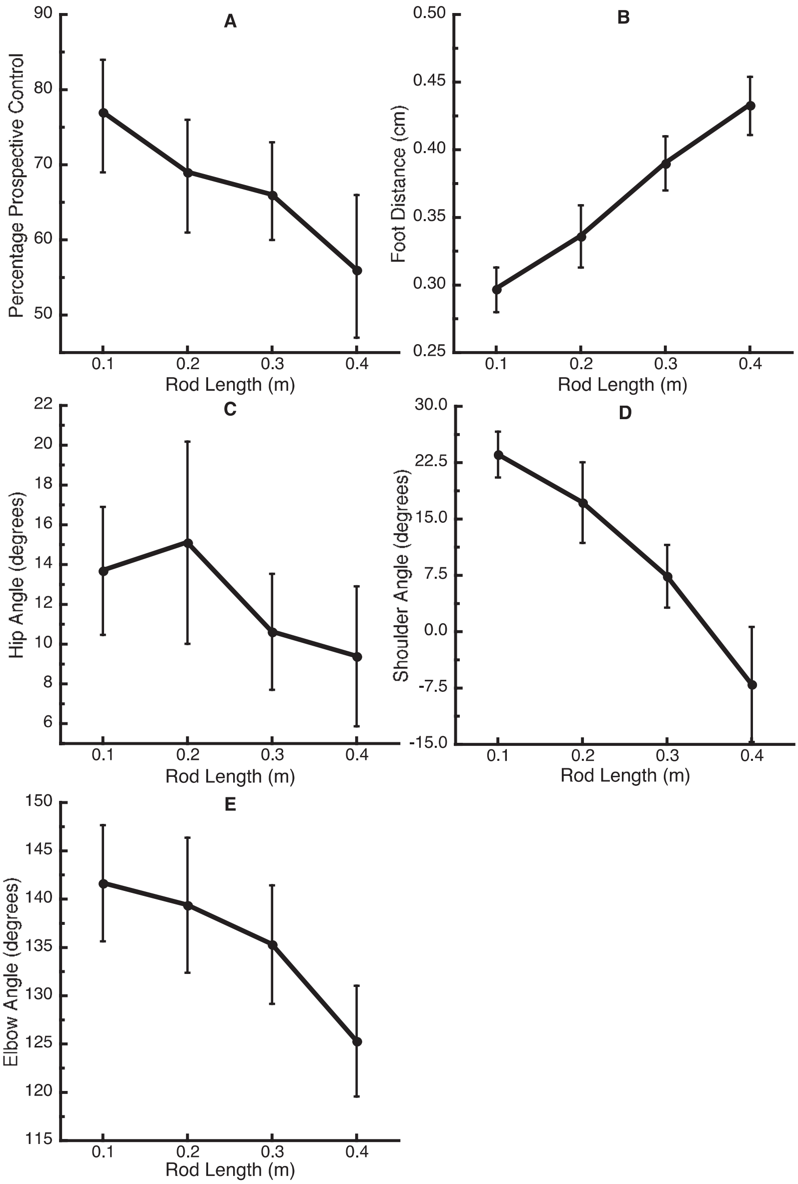

FIGURE 2 The means and accompanying confidence intervals (95%) for the significant main effects of rod length in Experiment 1: (a) percentage prospective control, (b) foot distance, (c) hip angle, (d) shoulder angle, and (e) elbow angle.

number of prospective trials decreases for longer rods and that this effect is stronger for rods with more weight, that is, rods that provide stronger postural constraints.

In sum, the number of prospective trials depends on properties of the rod and the age of the children. We next examined the mechanisms underlying the anticipatory change in behavior, which might explain why the number of prospective trials decreased in some conditions.

Foot distance. Deviating from task instructions could compromise some of our dependent variables. To ensure that the analyses tested prospective control, we included only trials in which children performed the task in a way they could show prospective control (trials scored with Items 1, 2, and 3 in the left column of Table 3). In total, there were 790 trials used in these analyses. Because of the omissions, 1 child had four missing cells and 4 children had one missing cell (Child 5 and Children 4, 8, 9, and 11, in Table 1, respectively). The remaining 16 children had no missing cells and were included in the analyses.[4] All the analyses were done on the averages for each condition.

Our first interest was in the variables that could predict the selected foot distance. We hypothesized that not only properties of the rod but also properties of the child would determine the foot distance. We performed a forward stepwise multiple regression with foot distance as the dependent variable on the averages. The independent variables were length, rod mass, maximum torque the rod can produce, moment of inertia, and the child's height, body weight, and age. The variables that explained significant, $F(3, 188) = 97.86, p < .001, R^2 = .61$, portions of the variance in the foot distance were (in order of importance): rod length, $t(191) = 16.35, p < .001$; height, $t(191) = -4.30, p < .001$; and weight, $t(191) = 2.56, p = .01$. There was a positive relation between foot distance and each of these variables. As expected, the foot distance mainly depended on rod length, which explained 56% of the variance. The other two significant variables were both properties of the children; however, those anthropometric variables contributed only marginally. Age did not contribute significantly to the explained variance (beyond its effect on height).

Foot distance on this same subset of trials was also analyzed by means of a three-way MANOVA with rod type (wood, aluminum, and steel) and rod length (0.1, 0.2, 0.3, and 0.4 m) as within-subject factors, and age (younger vs. older) as a between-subjects factor. Again, we performed the analysis on the averages for each condition of the 16 children. Two effects were significant: the effect of rod length, $F(3, 12) = 79.55, p < .001$, showing, as expected, that the children stopped farther from the table when they used longer rods (see Figure 2B); and the interaction be-

[4]The analyses done on this subset of the participants seems to be representative because similar results were obtained in analyses in which the missing values were imputed. The imputation was based on the EM procedure in SPSS that estimates the means, the covariance matrix, and the correlation of quantitative variables with missing values, using an iterative process. We assumed the data were normally distributed.

tween rod length and age, $F(3, 12) = 8.95$, $p < .005$. For each rod length, separate analyses using a Bonferroni correction showed a significant difference only for rods 30 cm long; younger kids selected a larger distance with those rods. The main effect of age was not significant. Moreover, rod mass did not affect the reaching distance.

We had manipulated mass because of its expected impact on the posture, independent of manipulations of length of the rod. From considerations regarding the shift of CM of body + rod, maximum torques in the joints, or wieldability of the rods, we had hypothesized that children would change the distance when rod mass changed. However, contrary to this expectation, children did not prospectively adapt the distance to the platform according to manipulations of mass. However, it still might be that the children adapted their posture systematically to manipulations of mass, a possibility to which we now turn.

Postural adjustments. We selected a different subset of trials to analyze postural angles. We used those trials on which the approach was acceptable, the distance was selected in one go, the posture was normal, and the rod was held in the right hand—that is, trials with items scored only in the left column of Table 3. This yielded a total of 737 trials.

Before we addressed how the individual angles changed, we first analyzed the underlying basis of the postural changes; that is, we asked whether posture reflects organized synergies. To determine whether the joints of the arm were organized as a synergy, we regressed shoulder angle against elbow angle for each child individually (cf. Newell & van Emmerik, 1989). The data in Table 4 show that, for most of the children, a considerable amount of the variance in shoulder angle is explained by the variance in elbow angle, indicating that the arm is organized as a synergy. The positive slope shows that, when the elbow is more extended, the upper arm is more anteflexed. For 2 children the explained variance was quite small.

To test for a second possible synergy, between hip and arm, we performed a multiple regression with hip angle as the dependent variable and shoulder angle and elbow angle as the independent variables, which were both entered at once. The analyses on individual children showed that only 2 of the children had explained variance larger than .35: $R^2 = .49$, $p < .005$, and $R^2 = .59$, $p < .0001$, respectively; both children were in the younger group. These low correlations over children suggest that the changes in the hip were independent from the changes in the shoulder and the elbow. In sum, the analyses on the postural synergies show that the arm is organized as a synergy for most of the children and that this synergy is independent of the hip.

We next examined the changes in the individual joints as a function of rod properties. All the analyses were done on the averages for each condition for each participant. There was 1 child who had four missing cells and 8 children who had one missing cell.[5] We performed a one-between, two-within-subjects MANOVA on the

[5]Similar analyses as presented were also performed when the missing cells were imputed (for a description of the procedure, see footnote 4). Because this affected the results to only a minor degree, we take the results presented here as representative.

TABLE 4
Regression Analyses Between Shoulder Angle and Elbow Angle for Experiment 1

Child	r^2	*df*	*F*	*p*	*Intercept*	*Slope*
1	0.51	1, 20	20.89	.000	–101	0.91
2	0.12	1, 23	3.04	.094	–39	0.38
3	0.68	1, 25	54.21	<.0001	–124	1.06
4	0.33	1, 19	9.53	.006	–49	0.57
5	0.61	1, 12	18.80	.001	–89	0.83
6	0.57	1, 18	24.15	.000	–70	0.62
7	0.77	1, 41	135.63	<.0001	–144	1.15
8	0.29	1, 35	14.16	.001	–77	0.64
9	0.36	1, 19	10.83	.004	–71	0.60
10	0.63	1, 47	78.48	<.0001	–97	0.79
11	0.76	1, 31	97.69	<.0001	–123	0.96
12	0.00	1, 30	0.10	.749	5	0.08
13	0.72	1, 44	112.57	<.0001	–148	1.11
14	0.48	1, 27	24.42	<.0001	–100	0.85
15	0.58	1, 46	64.15	<.0001	–147	1.10
16	0.31	1, 34	15.28	.000	–83	0.68
17	0.35	1, 46	24.79	<.0001	–94	0.74
18	0.33	1, 39	18.88	<.0001	–89	0.65
19	0.40	1, 51	33.58	<.0001	–93	0.79
20	0.46	1, 37	31.88	<.0001	–77	0.59
21	0.57	1, 51	66.85	<.0001	–124	0.97

angles. The hip angle was affected only by rod length, $F(3, 8) = 6.20, p < .05$. Figure 2C shows that the trunk leaned forward the most during the use of 20 cm rods and that the posture was more upright for the longer rods. Regarding the arm angles, rod length had a significant effect on shoulder angle, $F(3, 8) = 30.45, p < .001$; the shoulder was less anteflexed with longer rods and even retroflexed with the longest rod, as Figure 2D shows. The main effect of rod type was also significant, $F(2, 9) = 4.53, p < .05$, showing that the shoulder was less anteflexed with heavier rods (wood = 13°, 95% confidence interval: 9°–16°, aluminum = 10°, 95% confidence interval: 6°–15°, and steel = 8°, 95% confidence interval: 2°–14°). None of the other effects were significant. The multivariate analysis of variance (MANOVA) on the elbow angle showed only an effect of rod length, $F(3, 8) = 8.51, p < .01$; as can be seen in Figure 2E, the elbow was more flexed with longer rods.

Conclusions

We scored each trial according to a list of the qualitative criteria given in Table 2. Using these criteria, we analyzed behavior in the unfolding of a trial. The percentage of prospective trials was lower for longer rods, heavier rods, and younger children. Sets of trials in which anticipatory aspects of behavior could be tested were used for the analyses on foot distance and the postural angles. Children selected the distance to the platform according to rod length but not according to rod mass; however, their posture depended on both the length and mass of the rod. This indicates that the effects of mass on posture are not anticipated in the distance; hence, not all postural changes are prospectively reflected in the distance. With regard to age, this affected only the distance, a finding that we discuss further in the General Discussion section.

We found that the arm was organized as a synergy and organized independently from the hip. Shoulder angle was less anteflexed with heavier rods, which seems to be in agreement with the postural constraints related to both the shift in CM and maximum joint moment strength relations. However, our earlier findings pointed at the relative importance of the wieldability of the rods (Bongers et al., 2004). Hence, in Experiment 2 we increased the range of the wieldability of the rods to examine the relative importance of the constraints related to wieldability. Moreover, such a manipulation might improve the likelihood that distance was changed according to rod properties. In particular, we varied both the length and the mass distribution of the rods and asked whether these constraints affect the chosen distance to the platform and the posture with which the children displace the toy.

EXPERIMENT 2

We designed Experiment 2 to examine the relative importance of constraints related to the wieldability of the rod. To alter the wieldability of the rod, we manipulated both mass distribution and rod length. We achieved the manipulation of mass distribution by inserting weights into hollow tubing, either at the tip or at the handle. The postural constraints created by rods with weight at the tip should be similar to those created by steel rods, but the two may differ in how easily they can be wielded. In this experiment, we studied whether a manipulation of the wieldability in a larger range affects the prospective control, that is, the distance selected, and the posture with which the toy is displaced.

One difference between the rods used in Experiments 1 and 2 is in the location of the CM within the rod. Given a certain length, rods with a homogeneous mass distribution have their CMs located at the same position, independent of the mass of the rod. However, the position of the added mass determines the location of the CM when mass distribution is nonhomogeneous. The position of a rod's CM might be of importance for how the rod can be used to displace an object. For example, and with other things being equal, a rod with a heavy tip has more momentum at the tip. One can suppose that such momentum would benefit certain tasks; for example, hitting an object off the table should be easier with a rod with a heavy tip. However, when the task is not hitting but accurately moving and positioning the tip, other mass distributions might be better. For instance, it might be that a controlled movement of the tip requires the tip of the rod to be relatively lighter than the handle.

For the rods we used in this study we placed masses at different distances from the rotation point (the wrist). Rods with weight added at the tip have a larger moment of inertia, so if constraints related to wieldability are important, then these rods should most affect selected distance. To ensure that Experiment 2 was otherwise comparable to Experiment 1, we kept the torques that the rod could produce in a similar range. Remember that we associate torque with postural constraints related to the shift in CM and to muscle strength necessary to hold the rod.

As noted already, previous research has shown that adults are sensitive to changes in mass distribution of rods (for an overview, see Turvey & Carello, 1995) and are able to judge whether a rod with a certain distribution is appropriate for a certain task (cf. Wagman & Carello, 2001). Beak, Davids, and Bennett (1999) found that experienced adult tennis players who were asked to select a racket to strike a ball to a maximum distance selected rackets that had more weight placed at the tip than at the handle. However, when engaging in a similar task, 10-year-old children had more difficulty selecting the appropriate racket.

Testing rods that differ in mass distribution enabled us to evaluate the relative importance of postural constraints related to shift of CM and maximum joint torque and to wieldability of the rods. Any difference between the results of Experiment 1 and Experiment 2 will reveal the relative importance of those aspects of the task.

Method

The setup of Experiment 2 was similar to that of Experiment 1; the only differences were in the participants, the types of rods used, and some details of the experimental design.

Participants. Twenty-two preschoolers participated; 3 were girls, and 19 were boys (see Table 1). The children were divided into two age groups; the 10 younger children ranged in age from 2 years 2 months to 3 years 2 months (M age = 969 days), and the older children ranged in age from 3 years 3 months to 4 years 1 month (M age = 1,343 days). The children were from the same day-care center as the children in Experiment 1.

Materials. The rods varied in length from 0.3 m to 0.6 m with 0.1 m increments. The rods had to be longer in this experiment than in Experiment 1 because it is difficult to create differences in mass distribution in rods of 10 cm. The rods were made of PVC tubing with a diameter of 2.2 cm. To manipulate the mass distribution, a lead weight of 100 g was inserted into the tube. Three types of rods were constructed in this way: (a) no weight inserted, (b) one weight inserted at the handle, and (c) one weight inserted at the tip. The tubing was painted white, and attached to it was a handle 6.5 cm long and 1.2 cm in diameter. A small PVC disc separated the tubing and the handle. The characteristics of the rods are presented in Table 5.

TABLE 5
Characteristics of the Rods Used in Experiment 2

Length (m)	*Type*	*Mass (g)*	*Moment of Inertia (kgm^2)*	*Maximum Torque (Nm)*
0.30	No weight	41	0.00289	0.108
0.40	No weight	49	0.00561	0.169
0.50	No weight	55	0.00970	0.244
0.60	No weight	55	0.01542	0.333
0.30	Weight handle	125	0.00327	0.125
0.40	Weight handle	154	0.00598	0.186
0.50	Weight handle	184	0.01006	0.261
0.60	Weight handle	215	0.01579	0.350
0.30	Weight tip	346	0.01848	0.538
0.40	Weight tip	436	0.03104	0.720
0.50	Weight tip	524	0.04669	0.902
0.60	Weight tip	616	0.06622	1.099

Design. There were 20 children who performed five experimental sessions and 2 children who performed four sessions. Each session consisted of 12 trials: the combinations of three rod types and four rod lengths, in a random order. The sessions were performed on separate days within a 3-week period. There was a total of 1,294 trials because 4 trials were omitted because of technical problems. Three participants were removed because their performance deviated too much from the behavior of the other participants. One of those 3 was too often distracted during the experiment, and the other 2 did not point the rod sufficiently upward during the approach phase. After removing the data of those 3 participants, we had 1,123 trials performed by 19 children.

Results and Discussion

Behavioral analysis. Again we started our analyses with an examination of the alternative strategies children used to complete the task, which revealed roughly the same alternative behaviors as were found in Experiment 1. The only difference was that the number of two-handed trials was relatively large for the rods with weight at the tip.

We analyzed the percentages of trials in which participants showed prospective control (trials scored with Items 1, 2, and 3 in the left column of Table 3). We performed a three-way MANOVA on these percentages with rod type (no weight, weight at the handle, and weight at the tip) and rod length (0.3, 0.4, 0.5, and 0.6 m) as within-subject factors, and age (younger vs. older) as a between-subjects factor. Only the main effect of age was significant, $F(1, 17) = 5.70$, $p < .05$, showing that younger children had fewer trials in which they showed prospective control than older children (young = 64%, 95% confidence interval: 59%–70%, and old = 74%, 95% confidence interval: 68%–80%). None of the other effects were significant, showing that, unlike in Experiment 1, rod properties did not affect the percentage of prospective trials. Before we further addressed this difference between experiments, we examined whether mass distribution affects other aspects of prospective control, for instance, the selected distance.

Foot distance. For the analyses of foot distance, we used the trials in which the children could show prospective control (i.e., trials scored with Items 1, 2, and 3 in the left column of Table 3), which comprised 770 trials in total. We performed the analyses on the averages for each child and each condition. Data from 2 children were omitted because they had a missing cell; thus, analyses were done on the remaining 17 children.

As in Experiment 1, we started with a stepwise multiple regression in which foot distance was regressed onto rod length, place of the weight, rod mass, maximum torque, moment of inertia, and child's body height, body weight, and age. The variables that explained a significant, $F(3, 200) = 146.28$, $p < .001$, $R^2 = .69$, portion of the variance in the foot distance were (in the observed sequence): rod length, $t(200) = 18.79$, $p < .0001$; age, $t(200) = 4.21$, $p < .0001$; and body weight, $t(200) = 2.49$, $p < .01$. All the significant contributors had a positive relation with foot distance. As expected, the foot distance depended primarily on rod length; the proportion of explained variance for rod length alone was .55. The other significant variables were properties of the children.

We also analyzed the foot distance by means of a three-way MANOVA with rod type (no weight, weight at the handle, and weight at the tip) and rod length (0.3, 0.4, 0.5, and 0.6 m) as within-subject factors, and age (younger vs. older) as a between-subjects factor. The analysis was done on the 17 children who had no missing cells. Two main effects were significant: rod length, $F(3, 13) = 85.06$, $p < .001$, showing, as expected, that participants stopped farther from the table when they used longer rods (see Figure 3A); and age, $F(1, 15) = 8.53$, $p = .01$, showing that older children stopped farther from the table than did younger children. The interaction between those variables was also significant, $F(3, 13) = 4.36$, $p < .05$. Post hoc tests with Bonferroni correction showed that, for the two shortest rods, there was no difference in foot distance between the younger and older children, whereas for the longest rods, this difference was significant: $t(15) = -3.62$, $p < .005$, and $t(15) = -3.42$, $p < .005$, respectively.

The adaptation of foot distance only to rod length but not to rod type indicated that the children prospectively controlled their actions according to some, but not all, properties of the rod. Manipulations of mass distribution did not affect the selected distance. An analysis with missing values imputed showed the same results. However, children of different ages selected the distance differently, depending on the length of the rod. Before we further interpreted this finding we looked at the postural adaptations that accompany the adjustments in foot distance.

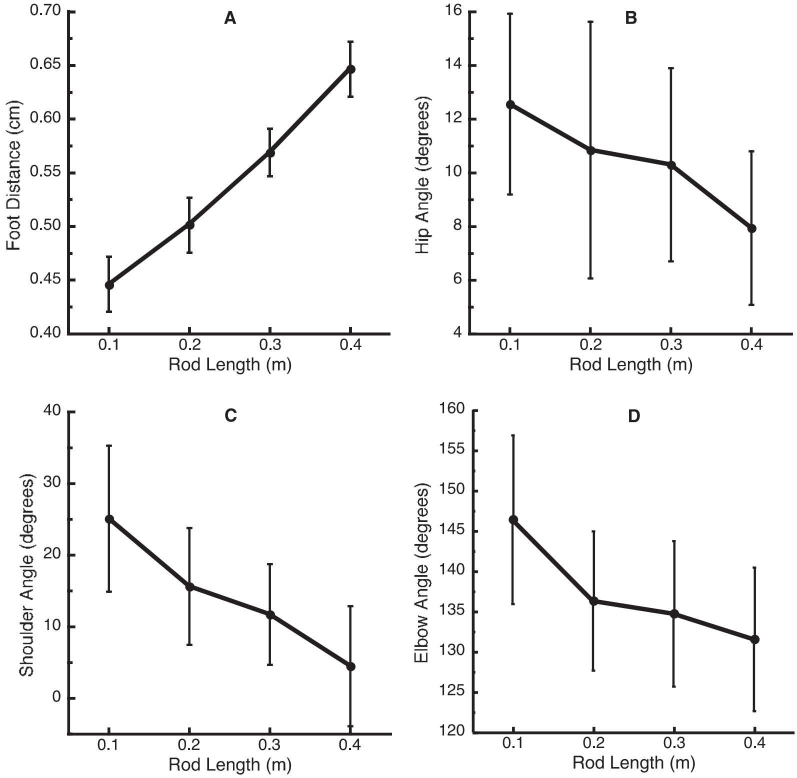

FIGURE 3 The means and accompanying confidence intervals (95%) for the significant main effects of rod length in Experiment 2: (a) foot distance, (b) hip angle, (c) shoulder angle, and (d) elbow angle.

Postural adjustments. We started with an examination of the synergies in which the posture was organized. Again, we performed regression analyses on the arm angles. As can be seen in Table 6, the shoulder angle and the elbow angle covaried for all of the children. Only 3 of the 19 children had an r^2 less than .5. This indicates that the arm was organized as a synergy; when the elbow extends, the upper arm is more anteflexed. However, the synergy in the arm was relatively unrelated to the hip angle; when we regressed hip angle onto shoulder angle and elbow angle, we noted that 2 children had an explained variance of .42 (both children had $ps < .0005$), and all the other children had smaller proportion of explained variance.

We also analyzed the three postural angles with three-way MANOVAs. As in Experiment 1, we performed those analyses on the trials with items only scored in the left column of Table 3 (a total of 697 trials). All the analyses were done on the averages for each condition for each child. Seven children had a missing cell,

TABLE 6
Regression Analyses Between Shoulder Angle and Elbow Angle
for Experiment 2

Child	r^2	*df*	F	*p*	*Intercept*	*Slope*
1	0.71	1, 24	58.42	<.0001	–128	1.06
2	0.80	1, 32	127.12	<.0001	–141	1.12
3	0.55	1, 28	34.14	<.0001	–89	0.81
4	0.63	1, 30	51.19	<.0001	–115	0.92
5	0.69	1, 35	78.67	<.0001	–111	0.93
6	0.77	1, 25	81.75	<.0001	–118	1.06
7	0.69	1, 39	85.99	<.0001	–119	0.99
8	0.684	1, 41	88.72	<.0001	–104	0.85
9	0.33	1, 29	13.93	.001	–57	0.48
10	0.78	1, 38	134.18	<.0001	–148	1.19
11	0.65	1, 43	80.37	<.0001	–89	0.77
12	0.52	1, 32	34.49	<.0001	–138	1.08
13	0.71	1, 38	91.54	<.0001	–119	1.01
14	0.53	1, 45	51.65	<.0001	–84	0.72
15	0.74	1, 36	103.07	<.0001	–165	1.28
16	0.40	1, 37	24.83	<.0001	–45	0.46
17	0.67	1, 34	67.92	<.0001	–90	0.83
18	0.48	1, 32	29.35	<.0001	–88	0.74
19	0.75	1, 41	123.17	<.0001	–116	0.99

so the analyses were done on the remaining 12 children. In our review of the results, we note when ANOVAs with imputed values (see footnote 4) yielded different results.

The analysis of hip angle showed a significant effect of rod length, $F(3, 8) = 6.13, p < .05$. As shown in Figure 3, the posture was more upright with longer rods. No other effects were significant.

The shoulder angle showed two significant main effects: The shoulder was most anteflexed with rods with no weights and was least anteflexed with rods weighted at the handle, $F(2, 9) = 4.26, p = .05$ (no weight = 17°, 95% confidence interval: 8°–25°, weight at handle = 12°, 95% confidence interval: 5°–19°, weight at tip = 14°, 95% confidence interval: 6°–22°). The other effect was that the shoulder was more anteflexed with shorter rods, $F(3, 8) = 6.44, p < .05$ (see Figure 3). This latter effect showed up also as significant in interaction with age, $F(3, 8) = 4.44, p < .05$; however, post hoc tests were not significant under Bonferroni restrictions.

For the elbow angle, the main effect of rod length was again significant, $F(3, 8) = 14.25, p = .001$. The means show that the elbow was more flexed with the longer rods, as can be seen in Figure 3. Two interaction effects were significant: the interaction between rod type and rod length, $F(6, 5) = 48.59, p < .001$, and the interaction among rod type, rod length, and age, $F(6, 5) = 13.54, p < .01$. However, both these effects disappeared when the analysis was performed on the data set with the imputed data. The averaged pattern of the 7 participants who had missing cells obviously deviated from the pattern of the other participants. Therefore, we do not further report these two interaction effects.

Conclusions

In this experiment we varied length and mass distribution of the rods to examine the relative importance of rod wieldability for the selected distance and the posture. A manipulation of the mass distribution of the rods affects the wieldability—the resistance to rotational acceleration varies with the place of the CM—and the torques that the rod creates. We expected that differences in torques and wieldability might necessitate using different postures to displace the object. The underlying postural organization (i.e., the synergies) was similar for Experiments 1 and 2, apparently independent from the combination of postural and movement constraints. With respect to posture, we found, in general, similar results in Experiments 1 and 2, suggesting that the manipulation of wielding constraints over a larger range—the main difference between rods of Experiments 1 and 2—did not affect the posture. As in Experiment 1, only shoulder angle depended on length and mass properties; the shoulder is not least anteflexed with tip-weighted rods, which would be expected on the basis of torque-related constraints alone, but with handle-weighted rods, which was expected from the wieldability hypothesis. Hence, constraints related to wieldability were more important when they were manipulated over a larger range. However, the other postural angles were not changed in a way predicted by the wieldability hypothesis. Shoulder angle was most anteflexed with nonweighted rods, showing that heavier rods (added weight at handle or tip) yielded less anteflexion, which is in agreement with Experiment 1. With regard to selected distance, not all postural variations were reflected in the distance, as in Experiment 1, indicating that not all affordance-related tool properties are anticipated. We discuss the effects of age in the next section.

GENERAL DISCUSSION

We were interested in how children's sensitivity to affordance-related tool properties develops. In two experiments, young children used a rod as a tool; they displaced a toy with the tip of the rod. To determine how the action was affected by properties of the rod, we measured the selected distance to the platform and the posture at the onset of toy displacement, along with a variety of qualitative performance characteristics. We took the distance as an indicator of prospective control, whereas posture was taken as an indicator of action characteristics that needed to be anticipated. Rod length, mass, and mass distribution were varied in the two experiments. To study developmental changes, we distinguished children who differed in age.

We argued that a rod's kinetic properties (i.e., properties related to mass) require changes in posture that ought to be anticipated in the selected distance. We analyzed selected distance and posture in trials on which children could show prospective control. We found that not all postural changes were prospectively reflected in the distance; distance was affected only by rod length, whereas posture was affected by length and mass. The changes in posture were not random; that is, posture in the arm was organized as a synergy. In Experiment 1, postural changes were in agreement with what could be expected from torque-related constraints, whereas postural changes in Experiment 2 were in agreement with what could be expected from constraints related to wieldability. Those systematic postural changes could be reflected in the distance. In the remainder of this section we further consider these findings in the context of two main questions: (a) Which tool properties determine affordances? and (b) Are there changes over age in the tool properties that determine affordances? Finally, we discuss the findings in broader perspectives of development of affordances and tool use.

To start, we argued that affordances in our task depend not simply on rod length but also on the posture with which the rod can be controlled. We tried to manipulate posture by varying postural constraints related to torque and its effects on shifts in CM, demands on muscle strength, and constraints related to the wieldability of the rod. In Experiment 1, shoulder angle changed according to what we expected from postural constraints: There was less anteflexion with stronger constraints. In Experiment 2, in which the wieldability of the rod was manipulated in a large range, shoulder angle changed in a different way: Rods that were most difficult to wield required relatively more anteflexion. Hence, both postural and movement constraints determine the affordances. A major question was whether the affordances with the rods were perceived. We argued that affordances can be said to be perceived when actions are prospectively modified, which we measured with the selected distance. We found that not all postural changes were prospectively reflected in the selected distance; the angles in the arm depended on rod mass, whereas foot distance did not. Therefore, we conclude that not all postural adaptations are prospectively reflected in the distance. In short, only variations in length affected the perceived affordances, whereas variations in mass and mass distribution were not perceived as changing the affordances. This implies that acting on all the relevant affordance-related tool properties needs to be learned.

We assume that learning to perceive these affordances goes hand in hand with learning to control the rod; we found more trials with prospective control for older children. The qualitative criteria on the basis of which prospective control trials were distinguished showed many items for which children either wielded the rod to explore action possibilities or were confined in their actions because they had difficulty controlling the rod. In other words, children were learning how to constrain the action system, which is essential for performing goal-directed actions. For example, Thelen and colleagues (Corbetta & Thelen, 1995; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Thelen, Corbetta, & Spencer,

1996) have reported that infants in their first year explore the intrinsic dynamics of the action system in order to learn goal-directed reaching. This indicates that the processes underlying the development of tool use seem to be similar to the processes of motor development.

As mentioned in the beginning of this article, in earlier work (Bongers et al., 2003) we asked adults to perform a similar task. In those experiments, rod length explained most of the variance, but small and reliable differences in both distance and posture depended on mass and mass distribution. The findings with adults showed that distance anticipated postural changes. Compared with adults, children prospectively modified the distance to only one characteristic of the rod—length. Adaptations in posture that depended on the mass of the rod were not reflected in the distance. Thus, results on distance showed that, unlike adults, children prospectively modify their behavior only to changes in geometrics and not to changes in the dynamics of the body + rod system.

The difference between adults and children indicates the presence of developmental differences in this tool-using behavior. To determine whether there were any age differences in the tool properties that affected affordances, we compared children of two age groups: one group roughly from 2 to 3 years old, and another group roughly from 3 to 4 years old. In several analyses we found statistical differences between the behaviors of children in these age groups. However, the results do not present an unambiguous developmental trend. For instance, in Experiment 1 younger children stopped farther from the table than older children, and this difference was larger for longer rods. However, in Experiment 2 younger children stopped closer to the table than older children. Moreover, in Experiment 2 we found effects of age on both the distance and the posture, whereas for Experiment 1 age affected only the distance. Taking these results together showed no clear pattern in the changes of behavior over age. It is obvious that, over the course of development, the perceptual system needs to be attuned to the full set of affordance-related tool properties. Our findings demonstrate that older children show more prospective control than younger children; however, like the younger children, they do not perceive the relevance of kinetic properties of the tool. More particularly, the larger number of prospective control trials for older children indicates that fine-tuning is developing in the age range in which we tested. However, our results also show that the fine-tuning is not complete; that is, the older children did not change the action prospectively to kinetic properties of the rods.

How do our findings fit in with other findings in the area of development of action? Lampl, Veldhuis, and Johnson (1992) showed that infant body growth occurs over very short time intervals (i.e., within a day) alternated with relatively static periods. The occurrence of short growth spurts indicates that infants and toddlers may be accustomed to sudden changes in properties of their action systems and that the nongrowth period following the spurt allows the children to learn how to control movements. However, with tools, the dynamics of the action system change and change back virtually instantaneously, implying that, for each trial, there is only a short time to attune to the new properties of the body + tool system. It might be that, because of this short calibration period, only a subset of the affordance-related tool properties are picked up, implying that prospective changes of actions can take place only to a part of the tool properties. In other words, perhaps younger children need more time to recalibrate their perceptual systems to tooling affordances. If this were the case, then the incomplete pickup of information follows from not being able to immediate recalibrate actions; the calibration speed would then be the capability that needs to be developed.

There is one issue, however, that deserves attention with regard to these conclusions. It might be that children did not need to adapt their distance in anticipation of postural constraints because the allowed variability in positioning the rod endpoint was rather large. For example, the size of the to-be-displaced toy was large compared with the expected magnitude of distance effects based on postural constraints. When a relatively large variability in the endpoint is allowed, there is less need to adapt the distance to the table to adjustments in the posture. This underconstraining of endpoint precision is a possible explanation of why we did not find effects of mass and age. However, in our earlier adult experiments (Bongers et al., 2003), the size of the object that had to be displaced was also much larger than the adaptations in the selected distance to the platform, but we did find that manipulations of the dynamics affected chosen distance. We see no reason to assume that those effects would not turn up in the experiments with children reported here. However, an important methodological point for future research is to tighten the task constraints so that the effects of organismic and environmental constraints cannot be absorbed by variations not captured by dependent variables (Bongers et al., 2004).

Finally, the view on tool use that we adopted here is a radical departure from more traditional accounts that tend to focus on mainly cognitive problems that a tool presents to the child (cf. Lockman, 2000). According to those views, tool use is a special case of object manipulation; that is, tool use manifests a certain degree of cognitive complexity in that it is an indirect means of goal attainment. In other words, the tool must be incorporated into an action, which involves intermediate steps in an action plan. For example, several investigators have presented stage models of the development of a tool-using skill (Connolly & Dalgleish, 1989, 1993; McCarty et al., 1999). All those models are strictly defined at the cognitive level and distinguish several stages in the developmental route of a child who masters a tool-using skill. For each of those stages, new processes are added to explain the more complex behavior of the child. However, those models do not address aspects concerning the action, such as limitations in the movements of the limbs or differences in forces when handling a filled spoon compared with an empty spoon. We argue that such cognitive-stage models would benefit from taking into account the action problem that a child needs to solve when using a tool (cf. Hirose, 2002; Lockman, 2000; Smitsman & Bongers, 2003; for similar arguments, see Thelen et al., 2001). For example, Steenbergen et al. (1997) investigated how young children used a spoon to scoop rice when the orientation between stem and bowl was manipulated. The results showed that the grip used and the variation of the position of the children's grip on the spoon depended on the type of spoon. The action problem is to control the relation between bowl and rice, and the degrees of freedom in the action system were constrained by spoon characteristics in realizing that relation. Similarly, in our experiments, constraints on action-system degrees of freedom depended on the properties of the rod used to displace the toy.

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REFERENCES

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Children Development, 62*(3, Serial No. 251).

Adolph, K. E., & Aviolo, A. M. (2000). Walking infants adapt locomotion to changing body dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1148–1166.

Adolph, K. E., Eppler, M. A., & Gibson, E. J. (1993). Development of perception of affordances. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 8, pp. 51–98). Norwood, NJ: Ablex.

Barger, V. D., & Olsson, M. G. (1995). *Classical mechanics: A modern perspective* (2nd ed.). New York: McGraw-Hill.

Bates, E., Carlson-Luden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavior and Development, 3,* 127–140.

Beak, S., Davids, K., & Bennett, S. (1999). Perception of affordances of haptic information in children and adults. In M. A. Grealy & J. A. Thompson (Eds.), *Studies in perception and action V* (pp. 215–218). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Bongers, R. M., Michaels, C. F., & Smitsman, A. W. (2004). Variations of tool and task characteristics reveal that tool use postures are anticipated. *Journal of Motor Behavior, 36,* 303–315.

Bongers, R. M., Smitsman, A. W., & Michaels, C. F. (2003). Geometrics and dynamics of a rod determine how it is used for reaching. *Journal of Motor Behavior, 35,* 4–22.

Chaffin, D. B., & Andersson, G. B. J. (1991). *Occupational biomechanics* (2nd ed.). New York: Wiley.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25,* 894–912.

Connolly, K., & Dalgleish, M. (1993). Individual patterns in tool use by infants. In A. F. Kalverboer, B. Hopkins, & R. Geuze (Eds.), *Motor development in early and later childhood: Longitudinal approaches* (pp. 174–204). Cambridge, England: Cambridge University Press.

Corbetta, D., & Thelen, E. (1995). A method for identifying the initiation of reaching movements in natural prehension. *Journal of Motor Behavior, 27,* 285–293.

Field, J. (1976). Relation of young infants' reaching behavior to stimulus distance and solidity. *Developmental Psychology, 12,* 444–448.

Gere, J. M., & Timoshenko, S. P. (1991). *Mechanics of materials* (3rd ed.). London: Chapman & Hall.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development.* New York: Oxford University Press.

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Gibson, J. J. (1986). *The ecological approach to visual perception.* Mahwah, NJ: Lawrence Erlbaum Associates, Inc. (Original work published 1979)

Hirose, N. (2002). An ecological approach to embodiment and cognition. *Cognitive Systems Research, 3,* 289–299.

Köhler, W. (1925). *The mentality of apes.* London: Kegan.

Lampl, M., Veldhuis, J. D., & Johnson, M. L. (1992, October 30). Saltation and stasis: A model of human growth. *Science, 258,* 801–803.

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development, 71,* 137–144.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35,* 1091–1101.

McKenzie, B. E., Skouteris, H., Day, R. H., Hartman, B., & Yonas, A. (1993). Effective action by infants to contact objects by reaching and leaning. *Child Development, 64,* 415–429.

Newell, K. M., & van Emmerik, R. E. A. (1989). The acquisition of coordination: Preliminary analysis of learning to write. *Human Movement Science, 8,* 17–32.

Pagano, C. C., Aten, T. R., & Alley, T. R. (1998, May). *Perceiving the lengths of rods wielded with and without vision.* Poster presented at the North American meeting of the International Society for Ecological Psychology, Hartford, CT.

Riach, C. L., & Hayes, K. C. (1990). Anticipatory postural control in children. *Journal of Motor Behavior, 22,* 250–266.

Shaw, R. E., Flascher, O. M., & Kadar, E. E. (1995). Dimensionless invariants for intentional systems: Measuring the fit of vehicular activities to environmental layout. In J. M. Flach, P. A. Hancock, J. Caird, & K. J. Vicente (Eds.), *Global perspectives on the ecology of human–machine systems* (pp. 293–357). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Shaw, R. E., & Turvey, M. T. (1981). Coalitions as models of ecosystems: A realist perspective on perceptual organization. In M. Kubovy & J. Pomeranz (Eds.), *Perceptual organization* (pp. 343–415). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Smitsman, A. W. (1997). The development of tool use: Changing boundaries between organism and environment. In C. Dent-Read & P. Zukow-Goldring (Eds.), *Evolving explanations of development: Ecological approaches to organism–environment systems* (pp. 301–329). Washington, DC: American Psychological Association.

Smitsman, A. W., & Bongers, R. M. (2003). Tool use and tool making: A dynamical developmental perspective. In J. Valsiner & K. J. Connolly (Eds.), *Handbook of developmental psychology* (pp. 172–193). London: Sage.

Solomon, H. Y., & Turvey, M. T. (1988). Haptically perceiving the distance reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 404–427.

Steenbergen, B., Van der Kamp, J., Smitsman, A. W., & Carson, R. G. (1997). Spoon handling in two- to four-year-old children. *Ecological Psychology, 9,* 113–129.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development, 64,* 1058–1098.

Thelen, E., Corbetta, D., & Spencer, J. P. (1996). Development of reaching during the first year: Role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1059–1076.

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences, 24,* 1–86.

Turvey, M. T. (1996). Dynamic touch. *American Psychologist, 51,* 1134–1152.

Turvey, M. T., & Carello, C. (1995). Dynamic touch. In W. Epstein & S. Rogers (Eds.), *Handbook of perception and cognition: Vol. 5. Perception of space and motion* (pp. 401–490). San Diego, CA: Academic.

Turvey, M. T., & Shaw, R. E. (1979). The primacy of perceiving: An ecological reformulation of perception for understanding memory. In L. G. Nilsson (Ed.), *Perspectives on memory research: Essays in honor of Uppsala University's 500th anniversary* (pp. 167–222). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Ulrich, B., Thelen, E., & Niles, D. (1990). Perceptual determinants of action: Stair-climbing choices of infants and toddlers. In J. E. Clark & J. H. Humphrey (Eds.), *Advances in motor development research* (Vol. 3, pp. 1–45). New York: AMS Press.

Van Leeuwen, L., Smitsman, A. W., & Van Leeuwen, C. (1994). Affordances, perceptual complexity and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 174–191.

Wagman, J. B., & Carello, C. (2001). Affordances and inertial constraints on tool use. *Ecological Psychology, 13,* 173–195.

Welter, T., Den Brinker, B. P. L. M., & Van Balkom, L. J. J. M. (1996). VidiPlus: Een automatisch video-analyse systeem voor bewegingsstudies [VidiPlus: An automatic video-analyses system for movement studies]. In B. P. L. M. den Brinker, P. J. Beek, A. P. Hollander, & R. T. Nieuwboer (Eds.), *Programma en uitgebreide samenvattingen van de Zesde Workshop Computers in de Psychologie* (pp. 145–147). Amsterdam: Vrije Universiteit Press.

Yonas, A., & Granrud, C. E. (1985). Reaching as a measure of infants' spatial perception. In G. Gottlieb & N. Krasnegor (Eds.), *The measurement of audition and vision during the first year of postnatal life: A methodological overview* (pp. 301–322). Norwood, NJ: Ablex.